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Human Factors Analysis of Postaccident Data: Applying Theoretical Taxonomies of Human Error

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Human error is involved in nearly all aviation accidents, yet most accident reporting systems are not currently designed around any theoretical human-error framework. As a result, subsequent postaccident databases generally are not conducive to traditional human factors analysis, making the identification of interventions extremely difficult. To address this issue, this study utilized 3 conceptual models of information processing and human error to reorganize the human factors database associated with U.S. Navy and Marine Corps aviation accidents between 1977–1992. All 3 taxonomies were able to accommodate well over three quarters of the pilot-causal factors contained in the database. Examinations of the recoded data revealed that procedural and response-execution errors were most common, followed by errors in judgment. However, judgment errors were more frequently associated with major than with minor accidents. Minor accidents, on the other hand, were associated more with procedural errors than were major accidents. This investigation demonstrates that existing postaccident databases can be reorganized using conceptual human-error frameworks, which may allow for previously unforeseen trends to be identified.

Human error has been implicated in 60% to 80% of both military and civil aviation accidents (O'Hare, Wiggins, Batt, & Morrison, 1994; Yacavone, 1993). Although the overall rate of aviation accidents has declined steadily during the past 20 years, reductions in human error–related accidents have not paralleled those related to mechanical and environmental factors. For example, U.S. naval aviation accidents

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attributable to either human or mechanical and environmental factors were nearly equal in 1977. Yet by 1992, accidents solely attributable to mechanical and environmental factors had been virtually eliminated whereas those attributable to human error had been reduced by only 50% (Shappell & Wiegmann, 1996). If aviation accidents are to be reduced further, more needs to be done to prevent the occurrence of human error and to design more error-tolerant systems.

One reason why aviation accidents attributable to mechanical failures have declined at a faster rate than those attributable to human error is that mechanical and engineering problems tend to be more tangible, and postaccident analyses of engineering problems tend to be more refined (Ferry, 1988). This situation is not surprising given the background of those in the field of accident investigation and the marked differences between mechanical and human factors engineering. For instance, most accident investigators are previous operators or designers with traditional engineering, rather than human factors, backgrounds. Likewise, engineering and mechanical failures are observable and quantifiable, whereas human factors issues tend to be perceived as somewhat qualitative and nebulous. As such, technological improvements are more readily identifiable than improvements based on human factors principles.

This is not to say that human factors analyses are not currently being performed or that they are without merit; rather, they are typically being performed by investigators from outside the fields of aviation psychology and human factors. As a result, the accident investigation and associated databases generally are not conducive to traditional human factors analysis (Edwards, 1981). This predicament is clearly reflected in the current U.S. naval aviation accident database. The method currently used by the U.S. Navy classifies aircrew errors using a scheme (designed by operators) that is loosely tied to a "who, what, and why" format. Although on the surface this framework would appear to answer many human factors questions, in actuality, it is not designed around any specific theoretical framework. This lack of a theoretical framework makes it extremely difficult to infer specific causes of human error. As such, the development of interventions to reduce the occurrence and consequences of aircrew errors is onerous.

OBJECTIVES OF THIS STUDY

This investigation represents an initial attempt to remedy these problems associated with classifying and analyzing postaccident, human-error data. Specifically, this study examines the utility of different conceptual human-error frameworks in organizing and analyzing human factors data contained in the U.S. naval aviation accident database. This project was the first step in the establishment of a research program whose ultimate aim is to develop a general framework for classifying, describing, and analyzing human errors associated with accidents. Because this investigation was the initial step in the process, several key issues were addressed during the study. These issues are discussed in the following sections prior to presenting our findings.

To Revamp or Develop Anew?

Ideally, the best way to develop a database conducive to human factors analysis would be to train accident investigators in human factors methods and gradually develop an entirely new database. However, there are practical constraints that arise when attempting to change existing systems. To simply abandon existing systems and replace them with new human factors databases is generally not feasible. To do so would forfeit all information available in the existing database (albeit limited) and would require several years for trends to emerge and be identified. Therefore, our first step was to use the existing naval aviation accident database, with known deficiencies, to test the utility of traditional human-error frameworks. Given the constraints, this approach seemed the most parsimonious and efficient way to identify putative interventions.

Identifying a Framework

Our initial search for a single framework, generally agreed upon by experts in the field of accident investigation, was ineffectual due to the numerous error taxonomies or frameworks that currently exist. Indeed, there appears to be as many taxonomic schemes as there are people interested in the topic (Senders & Moray, 1991). Nevertheless, three prominent frameworks were identified:

1. A traditional four-stage model of information processing.
2. A model of internal human malfunction derived from Rasmussen's (1982) Skills–Rules–Knowledge model.
3. A model of unsafe acts as proposed by Reason (1990).

We chose to use each of these three schemes to reorganize the existing accident database and to analyze trends in human error-related accidents. Each framework therefore is described briefly in the following sections.

Information processing model. Although not specifically a failure model, most models of human error are grounded in information processing theory. Therefore, any search for a framework to fit the accident database should begin with a traditional model of information processing. The four-stage model of information processing as described by Wickens and Flach (1988; see Figure 1) is

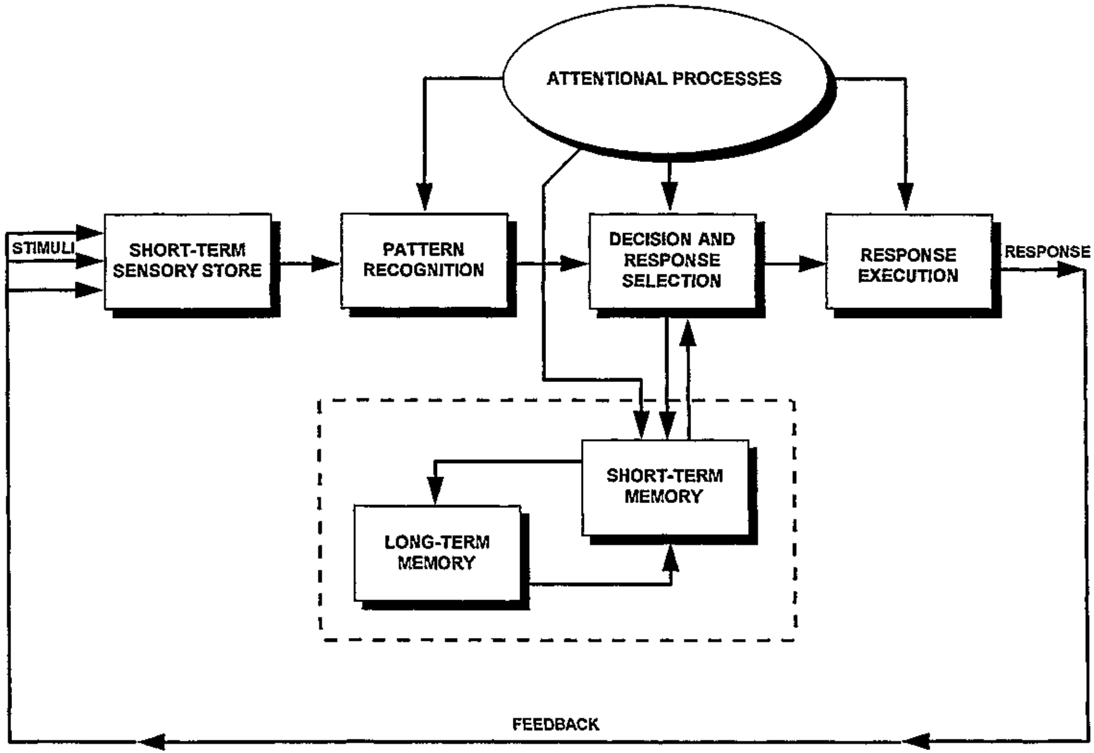

FIGURE 1 A four-stage model of information processing as described by Wickens and Flach (1988). From *Human Factors in Aviation* (p. 112) by E. L. Wiener and D. C. Nagel (Eds.), 1988, San Diego, CA: Academic. Copyright 1988 by Academic. Reprinted with permission.

representative of those in the literature. The principal feature of this model is the assumption that information progresses through a series of stages or mental operations that mediate between stimulus input and response execution. Various features of stimuli entering the senses are stored temporarily. These stored features then undergo a process of pattern recognition during which they are integrated into meaningful elements and identified. Next, a decision is made about how to react to the information. This decision then triggers the mapping and execution of a response. Processing during the latter three stages is influenced by individual attentional and memory resources. This entire sequence of operations involves a feedback loop which allows output to be monitored and adjusted.

A model of internal human malfunction. Rasmussen (1982) has outlined a more detailed model of the decision-making processes that has led to the development of a taxonomic algorithm for classifying information processing failures (see Figure 2). Similar to the traditional model of information processing, this model assumes that information is processed in stages that begin with the detection of cues in the environment and end with the execution of an action. The taxonomic algorithm as described by O'Hare et al. (1994) uses a six-step sequence to diagnose the underlying cognitive failure responsible for an error. The first and the last step are roughly equivalent to the short-term sensory store and response-execution stages of the traditional information processing model. The mediating four steps expand upon the remaining two stages (i.e., pattern recognition and decision or response selection). Specifically, the algorithm includes diagnostic, goal setting, strategy selection, and procedure adoption stages.

The model of unsafe acts. Reason (1990) has taken a slightly different approach to the classification of active failures (unsafe acts) that is particularly relevant here (see Figure 3). Unsafe acts are classified according to whether the behavior was intentional or unintentional. This does not mean that errors are either intended or unintended because individuals typically do not set out to make an error. Rather, it is the act and underlying decision processes that are either intentional or unintentional. Unintentional actions manifest themselves as slips that are due to attentional failures and lapses that are due to memory failures. Intentional actions, on the other hand, are classified as either mistakes or violations. Mistakes occur when previously learned rules and procedures are misapplied or inappropriate (rule-based errors) or simply don't exist (knowledge-based errors). Violations, similar to the previous three basic error forms described previously (slips, lapses, and mistakes), are unsafe behaviors. However they are not considered errors, per se. Rather, they represent a willful disregard for rules and regulations. Violations may be habitual parts of an individual's behavioral repertoire that are often tolerated

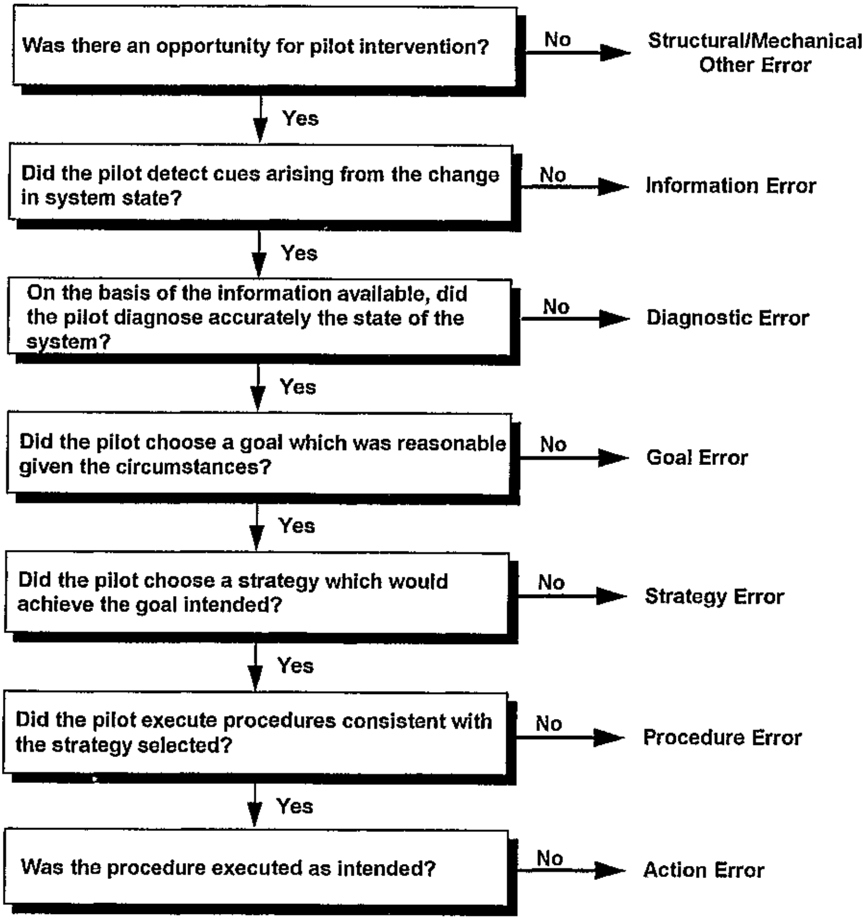

FIGURE 2 Rasmussen's (1982) taxonomic algorithm for classifying information processing failures as adapted by O'Hare et al. (1994). From "Cognitive Failure Analysis for Aircraft Accident Investigation," by D. O'Hare, M. Wiggins, R. Batt, and D. Morrison, 1994, *Ergonomics, 37,* p. 1863. Copyright 1994 by Taylor & Francis. Reprinted with permission.

by the organization (routine violations) or isolated, unacceptable departures from authority (exceptional violations).

Limitations of existing frameworks. To date, the use of conceptual frameworks to analyze human error has been largely academic (Ferry, 1988). In addition, the exact procedures for applying these frameworks to accident investigation have yet to be delineated, which has led some to question the practicality of such an approach (Ferry). Furthermore, conceptual frameworks of human error, such as

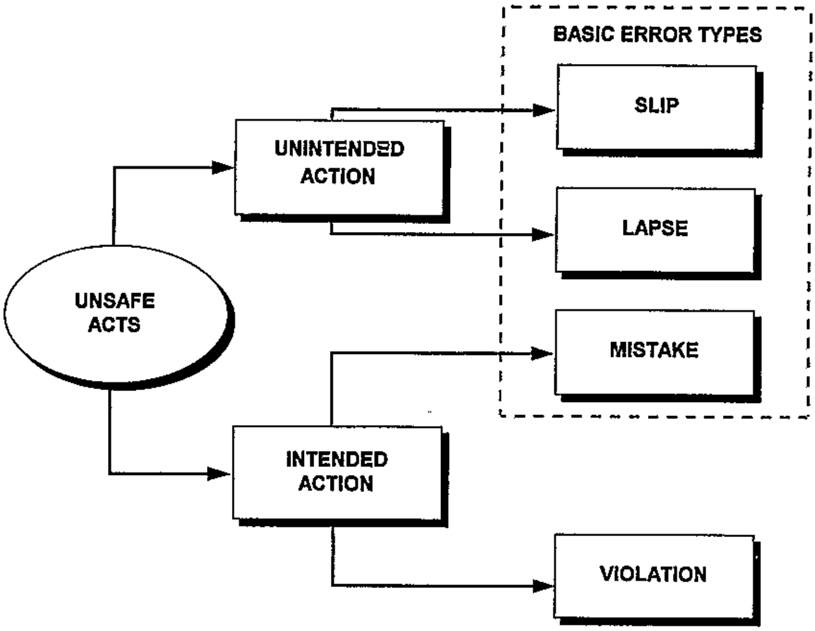

FIGURE 3 The model of unsafe acts. From *Human Error* (p. 207), by J. Reason, 1990, New York: Cambridge University Press. Copyright 1990 by Cambridge University Press. Reprinted with the permission of Cambridge University Press.

those describe previously, typically do not address accidents in their entirety (e.g., they do not take into account latent failures, such as supervisory errors, or contextual factors, such as the environmental conditions). Nevertheless, these models do provide a starting point for examining the direct causes of accidents (i.e., errors committed by the human operator). Moreover, initial attempts to apply an information processing approach to human failure in the cockpit have met with some success (O'Hare et al., 1994). Therefore, we decided that our first attempt at reorganizing the naval aviation accident database would involve using the three conceptual frameworks as previously described.

Specific Objectives

The specific objectives of this investigation were threefold. The first objective was to determine whether the current U.S. naval aviation accident database could be reorganized using the three conceptual taxonomies of human error (i.e., information processing, internal human malfunction, and unsafe acts). In other words, could the existing data be reclassified using these schemes or would a large portion of the data be lost because it was unclassifiable? The second objective was to determine whether reorganizing the database using these frameworks would reveal any meaningful trends in the types of human errors associated with aviation accidents. The third objective was to compare the utility of each framework in terms of reliability and comprehensiveness (i.e., was one model better than the others at classifying the data?).

METHOD

The Mishap Database

A comprehensive review of U.S. Navy and Marine Corps Class A, B, and C[1] flight and flight-related mishaps between January, 1977, and December, 1992, was conducted using database records maintained at the U.S. Naval Safety Center, Norfolk, Virginia. A total of 5,008 Class A, B, and C mishaps were reported during this period. Of these, 3,293 were attributed, at least in part, to human causes. The remaining accidents either were attributed to mechanical and environmental factors alone or were considered (a) beyond human limitations, (b) unavoidable, (c) the result of foreign object damage, or (d) of unknown origin.

Of the human-related accidents, we were particularly interested in accidents attributed, at least in part, to the pilot. A total of 1,970 pilot-related mishaps were identified, including 662 Class A mishaps, 266 Class B mishaps, and 1042 Class C mishaps. For each of these accidents, the actions or conditions of the pilot that contributed to the mishap had been previously classified by the original accident investigators using a standardized set of 289 possible pilot-causal factors. For each mishap, up to 3 pilot-causal factors were coded in the database. From these, a total 4,279 cases of pilot-causal factors were identified (1,629 cases were identified for Class A mishaps, 595 were identified for Class B mishaps, and 2,055 were identified for Class C mishaps).

Human Error Classification

Each of the 289 types of pilot-causal factor contained in the U.S. Naval Safety Center's database was independently coded by two judges using each of the three frameworks under investigation (i.e., information processing, internal human mal-

[1]The U.S. Navy classifies aviation mishaps according to the severity of the accident. Class A mishaps involve one or more of the following: (a) a total cost of $1,000,000, (b) total damage to an aircraft, (c) fatal injury, and (d) permanent total disability. Class B mishaps involves one or more of the following: (a) a total cost between $200,000 and $1,000,000, (b) permanent partial disability, and (c) hospitalization of 5 or more personnel. Class C mishaps involve either or both of the following: (a) a total cost between $10,000 and $200,000 and (b) 1 lost workday injury.

function, and unsafe acts). Coding disagreements were resolved by discussion. The reliability of the coding system for each framework was assessed by calculating values of Cohen's kappa between the pair of coders. Kappa is an index of agreement that has been corrected for chance (O'Hare et al., 1994). The obtained values were .935 and .777 for the internal human malfunction and unsafe acts models, respectively. Each of these values reflects an "excellent" level of agreement according to criteria described by Fleiss (1981, cited in O'Hare et al., 1994). The Kappa index obtained for the information processing model was .660, which is considered "good" by conventional standards.

RESULTS

Information Processing Model

Using the information processing model presented in Figure 1, we were able to classify 251 (86.9%) of the original 289 pilot-causal factors. The remaining 38 (13.1%) factors did not fit neatly into this framework. Factors that did not fit included planning for the flight, social variables (e.g., aircrew coordination), and the physiological or mental condition of the pilot (e.g., fatigue, spatial disorientation, loss of situational awareness.) When applied to the accident database, the model accounted for 3,450 (80.63%) of the original 4,279 cases of pilot-casual factors.

The distribution of cases that fit within the information processing model is presented in Table 1. Note that the percentages reported in the table are based upon only those factors that could be classified within the model. An examination of Table 1 reveals that errors in response execution were most frequent (45.48%), followed by decision or response-selection errors (29.54%), pattern recognition

TABLE 1
Information Processing Model: Percentage of Processing Errors Associated With Each Accident Type

	Mishap Type			
Error Type	*Class A*	*Class B*	*Class C*	*Total*
Sensory	4.65	1.26	1.94	2.84
Pattern recognition	10.64	13.42	18.43	14.87
Attention	10.56	4.40	5.63	7.28
Decision/response selection	34.83	33.12	24.59	29.54
Response execution	39.32	47.80	49.41	45.48

Note. Percentages in each category are based upon the total number pilot-causal factors that were classified within the model.

errors (14.87%), attention errors (7.28%), and sensory errors (2.84%). An examination of Table 1 also reveals differences in the distribution errors between major (Class A) and minor accidents (Class C). Decision or response-selection errors were more frequently associated with serious accidents (34.83%) than with minor accidents (24.59%). On the other hand, minor accidents were associated more with response-execution errors (49.41%) than were major accidents (39.32%). These observations were confirmed by the results of a chi-square analysis that tested the relation between error type and mishap severity (major vs. minor), $\chi^2(4, N = 2{,}973) = 112.09, p < .001$.

Model of Internal Human Malfunction

Of the original 289 pilot-causal factors, 264 (91.3%) were classified into one of the six error categories associated with Rasmussen's internal human malfunction framework. Similar to the information processing model, the factors that did not fit into this framework included planning for the flight, social variables (e.g., aircrew coordination), and the physiological or mental condition of the pilot (e.g., fatigue, spatial disorientation, loss of situational awareness). However, because this framework accommodated goal and strategy errors, it accounted for slightly more factors than the information processing framework (91.3% vs. 86.9%). When applied to the database, the model of human internal malfunction accounted for 3,784 (88.43%) of the original 4,279 cases of pilot-casual factors.

Table 2 presents the distribution of cases that fit within this scheme. The percentages reported in the table are based upon only those factors that could be classified within the framework. An examination of Table 2 reveals that procedural errors were most frequent (39.48%), followed by diagnostic errors (21.72%), strategy errors (12.95%), goal errors (11.55%), action errors (8.19%) and informa-

TABLE 2
Model of Internal Human Malfunction: Percentage of Processing Errors Associated With Each Accident Type

	Mishap Type			
Error Type	*Class A*	*Class B*	*Class C*	*Total*
Information	9.77	3.10	4.15	6.10
Diagnostic	24.15	21.12	20.04	21.72
Goal setting	15.08	9.88	9.32	11.55
Strategy selection	14.31	15.89	11.10	12.95
Procedure	31.73	40.89	44.99	39.48
Action	4.96	9.11	10.40	8.19

Note. Percentages in each category are based upon the total number pilot-causal factors that were classified within the model.

tion errors (6.10%). Again, however, differences between the distribution of errors were evident between severe and minor accidents. For major accidents, goal (15.08%) and strategy errors (14.31%) constituted a larger proportion of errors than they did for minor accidents (9.32% and 11.10% for goal and strategy errors, respectively). In contrast, minor mishaps were associated with more procedural errors than major accidents (44.99% vs. 31.73%), as well as with more action errors (10.40% vs. 4.96%). These differences in the distribution of error types across serious and minor accidents were significant, $\chi^2(5, N = 3{,}268) = 139.35, p < .001$.

Model of Unsafe Acts

Using the model of unsafe acts, we were able to classify 264 (91.3%) of the original 289 pilot-causal factors. Similar to the previous two frameworks, the factors that did not fit in the model of unsafe acts included social variables (e.g., aircrew coordination) and physiological or mental conditions of the pilot (e.g., fatigue, spatial disorientation, loss of situational awareness). Pilot-causal factors that were related to flight planning fit into the model of unsafe acts, which accounts for the slightly higher percentage of factors that fit into this model (91.3%) compared to the information processing model (86.9%). Both the model of unsafe acts and the model of human internal malfunction accounted for the same percentage of pilot-causal factors (91.3%). However, they did not account for entirely the same set of factors. The model of unsafe acts accommodated more flight-planning errors, whereas the model of internal human malfunction accommodate more sensory and information errors. When applied to the accident database, the model of unsafe acts accounted for 3,606 (84.27%) of the original 4,279 cases of pilot-causal factors, slightly less than the model of human internal malfunction (88.43%).

Of the cases of pilot-causal factors that fit within the model of unsafe acts (see Table 3), 74.54% were classified as intended actions (i.e., mistakes and violations), whereas 25.46% were classified as unintended actions (i.e., slips and lapses). The largest portion of errors were intended action mistakes (57.13%), followed by

TABLE 3
Model of Unsafe Acts: Percentage of Action Errors Associated With Each Accident Type

	Mishap Type			
Error Type	*Class A*	*Class B*	*Class C*	*Total*
Slip	13.08	13.66	15.32	14.28
Lapse	9.15	10.30	12.88	11.18
Mistake	54.92	60.20	57.86	57.13
Violation	22.85	15.84	13.94	17.42

Note. Percentages in each category are based upon the total number pilot-causal factors that were classified within the model.

violations (17.42%), slips (14.28%), and lapses (11.18%). An examination of Table 3 indicates the largest differences in the distribution of error types was again between severe and minor accidents. Violations were more frequently associated with major accidents (22.85%) than with minor accidents (13.94%). On the other hand, minor accidents were associated more with the three basic error types (slips, lapses, and mistakes) than were major accidents (see Table 3 for the breakdown of the distributions). These differences in error distributions between major and minor mishaps was significant, $\chi^2(3, N = 3{,}101) = 46.98, p < .001$.

DISCUSSION

Review of Findings by Objective

A primary objective of this investigation was to determine whether the current U.S. naval aviation accident database could be reorganized using three prominent conceptual taxonomies of human error (i.e., information processing, internal human malfunction, and unsafe acts). This objective met with considerable success. Nearly 87% of the original 289 pilot-causal factors fit within the information processing framework, which accounted for over 80% of the 4,279 cases of pilot-casual factors contained in the database. Approximately 91% of the pilot-causal factors fit within both the unsafe acts (Reason, 1990) and human internal malfunction models (Rasmussen, 1982), which accounted for over 84% and 88% of the 4,279 cases of pilot-causal factors, respectively. Although some information was lost, well over three fourths of the data was effectively categorized using each taxonomy.

The second question of interest was whether reorganizing the database using these frameworks would reveal any meaningful trends in the types of human errors associated with aviation accidents. Again, the answer was yes. Consistent trends in error distributions were observed across all three conceptual models. In general, accidents were primarily associated with procedural and response-execution errors, as well as mistakes. The second highest contributor was judgment error (i.e., errors in decision making, goal setting, and strategy selection, as well as intended violations of rules and regulations.) Furthermore, the latter type of error (i.e., judgment error) was associated more with major accidents than with minor accidents. On the other hand, minor accidents were associated more with the former error type (i.e., procedural errors) than were major accidents. These findings are similar to those recently found using a cognitive failure analysis of pilot errors associated with civilian aviation accidents (O'Hare et al., 1994). In general, it appears that major and minor accidents are due, at least in part, to two qualitatively different problems. This finding tends to dispel the old adage that minor accidents are just a "heart beat away" from catastrophe (i.e., that the difference is one of luck).

However, a more detailed analysis is needed to further investigate this apparent difference. Nevertheless, this finding clearly demonstrates the potential utility of human error analysis as outlined here.

Finally, the third objective of this study was to compare the utility of each framework in terms of reliability and comprehensiveness. All three scoring schemes used to code pilot-causal factors were reliable based on conventional standards. An excellent level of agreement between coders was obtained using the unsafe acts and internal human malfunction models. A somewhat lower level of agreement was obtained using the traditional four-stage model of information processing. Likewise, all three models accounted for well over three fourths of the data. However, the two contemporary error models accounted for slightly more pilot-causal factors than did the traditional four-stage information processing model. These differences are not too surprising given that the model of unsafe acts and the model of human internal malfunction are failure models that build upon the traditional information processing approach. The unsafe acts and internal human malfunction models accommodated slightly different types of pilot-casual factors; however, these two models were very comparable in terms of their reliability and comprehensiveness.

Future Directions

From an academic point of view, the ability of the three frameworks to reliably classify accident data was considered a success. However, from an applied point of view, several human factors remained unclassified. Factors that did not fit cleanly into these frameworks included planning for the flight, social variables (e.g., aircrew coordination), and physiological or mental condition of the pilot (e.g., fatigue, spatial disorientation, loss of situational awareness). These are important factors that need to be considered in order to gain a full understanding of the causes of accidents in general and aviation accidents in particular. Furthermore, this investigation focused only on pilot-causal factors. Other factors such as supervisory errors and contextual factors were not considered, nor would they have been accounted for using the three conceptual error taxonomies examined. If human factors issues affecting accidents are to be addressed in their entirety, a more comprehensive model which takes into account these additional factors must be used.

Once a comprehensive model has been identified, a relational database needs to be constructed to assess the interrelations among error types. A relational database would facilitate the testing of theories about the strength of the relation between latent factors and the occurrence of specific errors committed by operators. Similarly, a relational database would allow for a more refined analysis of the effects that one type of operator error (e.g., judgment error) has on the occurrence of another (e.g., procedural error). In essence, once a unifying framework is identified, the causal chain of events leading to an accident can be more easily inferred, intervention strategies more readily identified, and the tragic chain of events ultimately broken.

Finally, investigative techniques and documentation procedures compatible with whatever human factors framework is adopted must be developed. In doing so, the background and education of field investigators must be considered during the design processes. Most field investigators are prior operators and come from engineering and material science backgrounds. As a result, they are not generally familiar with psychological and human factors concepts. Therefore, if human factors databases are to be useful and effective, field investigators need to be educated about human factors analyses and provided with user-friendly tools to assist them during the investigative process.

SUMMARY AND CONCLUSIONS

This investigation demonstrates that postaccident data can be organized using traditional models of information processing and human error. This approach imposes a human factors structure to an otherwise nebulous database without the burden of reinvestigating the original mishap. Furthermore, this type of data analysis provides a theoretical framework for identifying and describing trends in the types of errors associated with accidents. The frameworks examined here, however, were not without their limitations, and therefore alternative frameworks should be considered before one is adopted. Once a comprehensive framework has been identified and applied, the development of interventions to reduce the occurrence and consequences of human error should be more readily forthcoming.

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